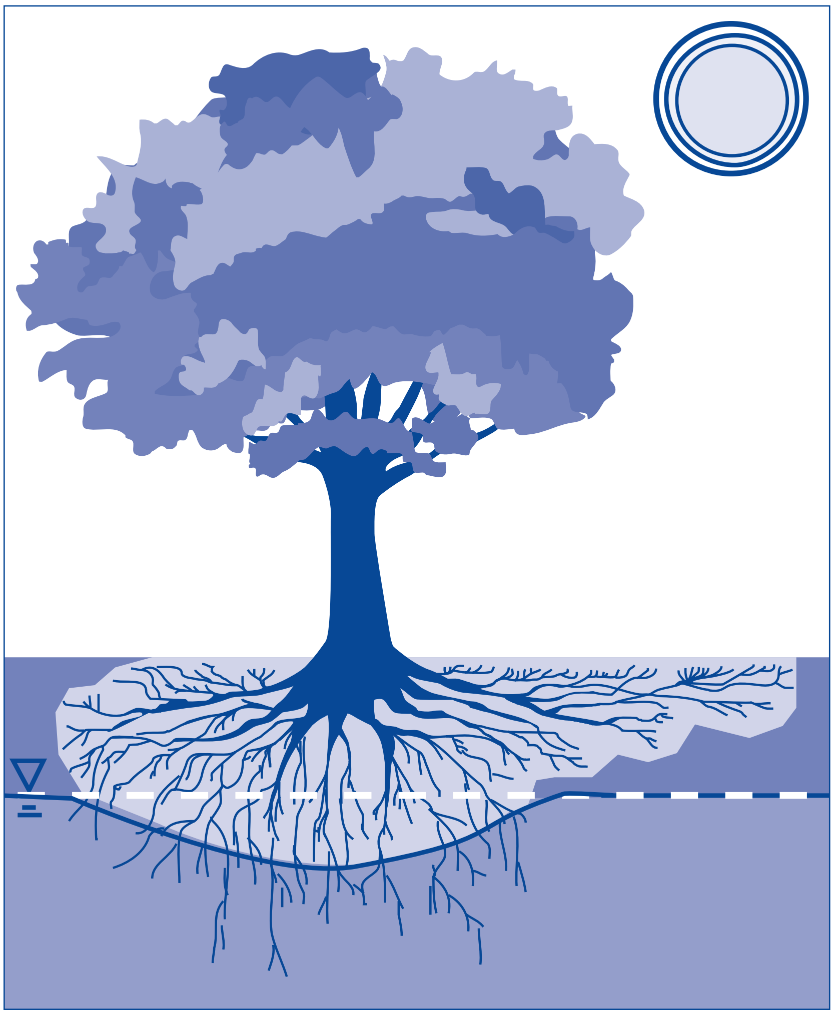
Decision Tree

Phytoremediation



December 1999

Prepared by
Interstate Technology and Regulatory Cooperation Work Group
Phytoremediation Work Team

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The 1999 ITRC Phytoremediation Work Team is made up of state regulators, industry representatives, a public stakeholder, and members of the EPA interested in implementing the use of phytoremediation.

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EXECUTIVE SUMMARY

Phytoremediation, a technology using plants to remediate or stabilize contaminants in soil, groundwater, or sediments, has recently received a great deal of attention from regulators, consultants, responsible parties, and stakeholders. Phytoremediation has become an attractive alternative to other cleanup technologies due to its relatively low-cost potential effectiveness and the inherently aesthetic nature of using plants to clean up contaminated sites. This focus on phytoremediation has led scientists and regulators to be concerned that this technology will be considered at sites that are not appropriate for its use.

The intent of this document is to provide a tool that can be used to determine if phytoremediation has the ability to be effective at a given site. It is designed to complement existing phytoremediation documents such as the USEPA's *Introduction to Phytoremediation*. It allows the user to take basic information from a specific site and, through a flowchart layout, decide if phytoremediation is feasible at that site.

The ITRC's Phytoremediation Work Team has provided separate decision trees for three types of contaminated media (i.e. soil, groundwater, and sediments). Along with each decision tree, additional basic information is provided and is intended to support the decision tree, allowing it to remain in as simple a form as possible.

In addition to the decision trees, a brief overview of various types of phytoremediation and a section on stakeholder concerns are included. A glossary of terms used in the phytoremediation field is also included as a resource to the user.

The ITRC Phytoremediation Work Team is working on a second document entitled *Technical Information and Regulatory Guidance for Phytoremediation of Organic Contamination*. The intention of this decision tree document is to provide a logical link between technology overview documents and the planned technical and regulatory document.

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1.0 INTRODUCTION

The Interstate Technology and Regulatory Cooperation (ITRC) Work Group is a state-led, national coalition of personnel from the regulatory and technology programs of more than 25 states; three federal agencies; and tribal, public and industry stakeholders. The organization is devoted to reducing barriers and speeding interstate deployment of better, more cost-effective, innovative environmental technologies. The ITRC forms work teams to focus on specific innovative environmental technologies. These work teams develop technology overview documents, technical and regulatory guidance documents, and special documents like this decision tree to assist in the implementation of innovative technologies.

The 1999 ITRC Phytoremediation Work Team is made up of state regulators, industry representatives, a public stakeholder, and members of the EPA interested in implementing the use of phytoremediation. This work team is continuing the efforts of previous ITRC work teams reviewing innovative technologies to remediate metals in soils.

One successful method to implement new technologies is to provide tools useful to regulators, industry, technology vendors, and public stakeholders. This decision tree was developed to aid interested parties (regulators, site owners, and stakeholders) in evaluating sites as candidates for phytoremediation. The background information required in the decision process should be available from the site characterization data. This decision tree document is a supplement to several additional phytoremediation documents that have already been published (see Section 6.0, Selected References). These documents will provide the reader in-depth background on the science and engineering mechanisms of phytoremediation.

Using the decision tree and the reference documents will assist regulators, site owners, technology vendors, the public, and stakeholders in determining if phytoremediation is applicable to a contaminated site. Phytoremediation is a new technology, and not all of its applications are well understood. This decision tree document provides the user some background information on phytoremediation, the unique terms used in phytoremediation, and decision trees based upon contaminated media type (groundwater, soil, and sediment). As more information on the application of phytoremediation is gained, this document will be updated.

The phytoremediation decision tree flowcharts are found on pages 11, 13, and 16. Additional information has been included to assist the user in navigating the decision tree flowcharts. The design of the decision tree flowcharts will assist the user in making a determination if phytoremediation is an applicable technology for a contaminated site. If the decision tree flowcharts indicate phytoremediation may be an applicable technology, more research will be needed to ensure a proper design of the system. Information on phytoremediation terminology and the types of plants and contaminants for which the technology is applicable have also been included.

1.1 Background

Phytoremediation is the name given to a set of technologies that use plants to remediate contaminated sites. Phytoremediation uses living plants for *in situ* and *ex situ* remediation of contaminated soil, sludges, sediments, and groundwater through contaminant removal, Degradation, or stabilization. Phytoremediation can be used to remediate various contaminants including metals, pesticides, solvents, explosives, petroleum hydrocarbons, polycyclic aromatic hydrocarbons, and landfill leachates. Phytoremediation has been used for point and nonpoint source hazardous waste control.

1.2 Types of Phytoremediation

The US EPA's *Phytoremediation Resource Guide* definition of the six types of phytoremediation and their application is listed below.

1.2.1 Phytoaccumulation

Phytoaccumulation, also called phytoextraction, refers to the uptake and translocation of metal contaminants in the soil by plant roots into the aboveground portions of the plants. Certain plants called hyperaccumulators absorb unusually large amounts of metals in comparison to other plants and the ambient metals concentration. These plants are selected and planted at a site based on the type of metals present and other site conditions. After the plants have been allowed to grow for several weeks or months, they are harvested. Landfilling, incineration, and composting are options to dispose of or recycle the metals, although this depends upon the results of the Toxicity Characteristic Leaching Procedure (TCLP) and cost. The planting and harvesting of plants may be repeated as necessary to bring soil contaminant levels down to allowable limits. A plan may be required to deal with the plant waste. Testing of the plant tissue, leaves, roots, etc., will determine if the plant tissue is a hazardous waste. Regulators will play a role in determining the testing method and requirements for the ultimate disposal of the plant waste.

1.2.2 Phytodegradation

Phytodegradation, also called phytotransformation, is the breakdown of contaminants taken up by plants through metabolic processes within the plant, or the breakdown of contaminants external to the plant through the effect of compounds, such as enzymes, produced by the plants. Pollutants are degraded, used as nutrients, and incorporated into plant tissues. In some cases metabolic intermediate or end products are re-released to the environment depending on the contaminant and plant species (see phytovolatization).

1.2.3 Phytostabilization

Phytostabilization is the use of certain plant species to immobilize contaminants in soil and groundwater through absorption and accumulation by roots, adsorption onto roots or precipitation within the root zone, and physical stabilization of soils. This process reduces the mobility of the contaminant and prevents migration to the groundwater or air. This technique can be used to re-establish a vegetative cover at sites where natural vegetation is lacking due to high metal concentrations. Metal-tolerant species may be used to restore vegetation to such sites,

thereby decreasing the potential migration of contamination through wind erosion, transport of exposed surface soils, and leaching of soil contamination to groundwater.

1.2.4 Phytovolatilization

Phytovolatilization is the uptake and transpiration of a contaminant by a plant, with release of the contaminant or a modified form of the contaminant to the atmosphere from the plant. Phytovolatilization occurs as growing trees and other plants take up water and organic and inorganic contaminants. Some of these contaminants can pass through the plants to the leaves and volatilize into the atmosphere at comparatively low concentrations. Many organic compounds transpired by a plant are subject to photodegradation.

1.2.5 Rhizodegradation

Rhizodegradation, also called phytostimulation, rhizosphere biodegradation, enhanced rhizosphere biodegradation, or plant-assisted bioremediation/degradation, is the breakdown of contaminants in the soil through microbial activity that is enhanced by the presence of the rhizosphere. Microorganisms (yeast, fungi, and/or bacteria) consume and degrade or transform organic substances for use as nutrient substances. Certain microorganisms can degrade organic substances such as fuels or solvents that are hazardous to humans and eco-receptors and convert them into harmless products through biodegradation. Natural substances released by the plant roots—such as sugars, alcohols, and acids—contain organic carbon that act as nutrient sources for soil microorganisms, and the additional nutrients stimulate their activity. Rhizodegradation is aided by the way plants loosen the soil and transport oxygen and water to the area. The plants also enhance biodegradation by other mechanisms such as breaking apart clods and transporting atmospheric oxygen to the root zone.

1.2.6 Rhizofiltration

Rhizofiltration is the adsorption or precipitation of contaminants onto plant roots or the absorption of contaminants into the roots when contaminants are in solution surrounding the root zone. The plants are raised in greenhouses hydroponically (with their roots in water rather than in soil). Once a large root system has been developed, contaminated water is diverted and brought in contact with the plants or the plants are moved and floated in the contaminated water. The plants are harvested and disposed as the roots become saturated with contaminants.

1.2.7 Applications

Phytoremediation applications (presented in Table 1-1, page 6, for organic compounds and Table 1-2, page 7, for inorganic compounds) are classified based on contaminant fate, degradation, extraction, containment type, or a combination of these (EPA document *Phytoremediation: Applications and Limitations*). These tables are to be used with the decision tree to determine if the contaminant to be treated can be used with the type of phytoremediation under consideration. In the soil-plant-atmosphere continuum, a specific contaminant can be remediated at specific points along this continuum by different phytoremediation mechanisms. This is shown in Figure 1-1 on page 4.

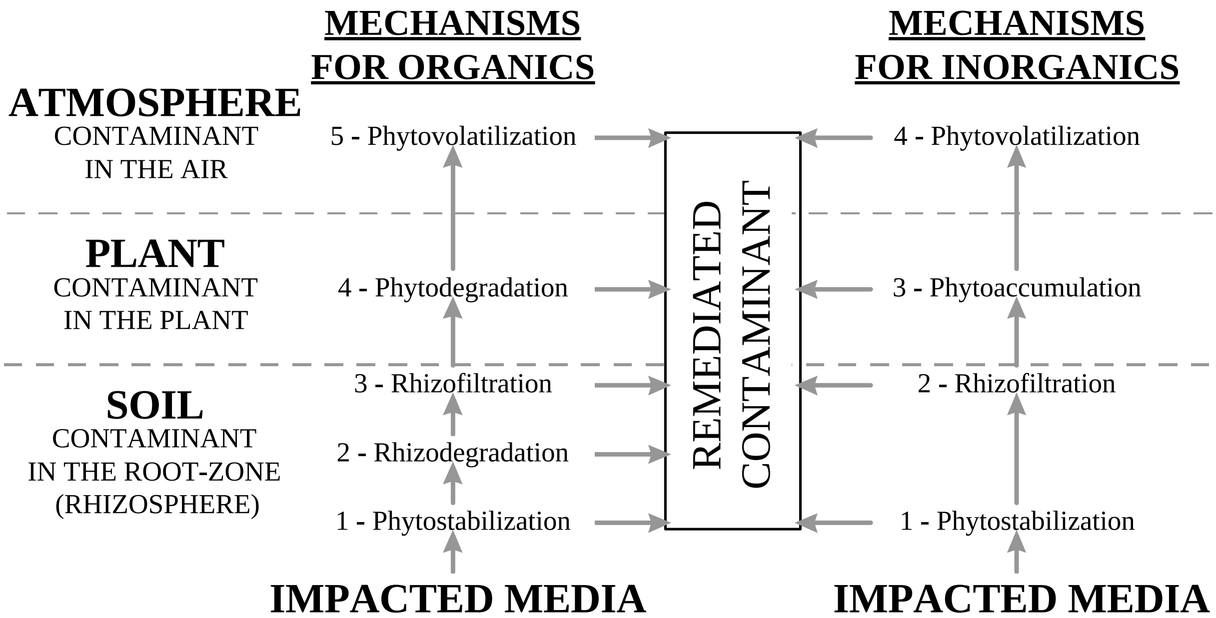


Figure 1-1: Contaminant Fate in the Soil-Plant-Atmosphere Continuum

1.3 Stakeholder Concerns

Phytoremediation technology has limitations and is not applicable for all sites. The site characterization process is important in determining if the contaminants of concern fit within the boundaries of phytoremediation technology. Stakeholder concerns with the technology must be addressed before a phytoremediation system is installed. This decision tree document addresses some of the concerns with this technology; however, other stakeholder concerns are beyond the scope of this document. Some of these concerns include:

- Toxicity and bioavailability of biodegradation products are not always known.
- Mobilization of degradation byproducts in groundwater or bioaccumulation in the food chain.
- Lack of research to determine the fate of various compounds in the plant metabolic cycle and to ensure that plant droppings and products manufactured by plants do not contribute toxic or harmful chemicals into the food chain.
- Scientists need to establish whether contaminants that collect in the leaves and wood of trees are released when the leaves fall in the autumn or when firewood or mulch from the trees is used.
- Harvested plants may require disposal as hazardous waste.
- Depth of the contaminants limits treatment. The treatment zone is determined by plant root depth. In most cases, it is limited to shallow soils, streams, and groundwater.
- Pumping water out of the ground and using it to irrigate plantations of trees may treat contaminated groundwater that is too deep to be reached by plant roots but raises concerns about the fate and transport of contaminants.
- Generally, the use of phytoremediation is limited to sites with lower contaminant concentrations and contamination in shallow soils, streams, and groundwater. However,

researchers are finding that the use of trees (rather than smaller plants) allows them to treat deeper contamination because tree roots penetrate more deeply into the ground.

- The success of phytoremediation may be seasonal, depending on location. Other climatic factors will also influence its effectiveness.
- If contaminant concentrations are too high, plants may die.
- Some phytoremediation transfers contamination across media (e.g., from soil to air).
- Phytoremediation is not effective for strongly sorbed contaminants such as PCBs.
- Phytoremediation requires a large surface area of land for remediation.
- Animals may damage plants and create a need to replant.

Table 1-1: Types of Phytoremediation for Organic Compounds

Type of Phytoremediation	*Process Involved*	*Contaminant Treated**
1 – Phytostabilization	Plants control pH, soil gases, and redox conditions in soil to immobilize contaminants. Humification of some organic compounds is expected.	Expected for phenols, chlorinated solvents (tetrachloromethane and trichloromethane), and hydrophobic organic compounds
2 - Rhizodegradation, phytostimulation, rhizosphere bioremediation, or plant-assisted bioremediation	Plant exudates, root necrosis, and other processes provide organic carbon and nutrients to spur soil bacteria growth by two or more orders of magnitude. Exudates stimulate degradation by mycorrhizal fungi and microbes. Live roots can pump oxygen to aerobes and dead roots may support anaerobes.	Polyaromatic hydrocarbons, BTEX, and other petroleum hydrocarbons, perchlorate, atrazine, alachlor, polychlorinated biphenyl (PCB), and other organic compounds
3 - Rhizofiltration or contaminant uptake	Compounds taken up or sorbed by roots (or sorbed to algae and bacteria)	Hydrophobic organic chemicals
4 - Phytodegradation or phytotransformation	Aquatic and terrestrial plants take up, store, and biochemically degrade selected organic compounds to harmless byproducts, products used to create new plant biomass, or byproducts that are further broken down by microbes and other processes to less harmful products. Reductive and oxidative enzymes may be used in series in different parts of the plant.	Munitions (TNT, DNT, HMX, nitrobenzene, picric acid, nitrotoluene), atrazine, halogenated compounds (tetrachloromethane, trichloromethane, hexachloroethane, carbon tetrachloride, TCE, tetrachloroethane, dichloroethane), DDT and other chlorine and phosphorus based pesticides, phenols, and nitrites.
5 - Phytovolatilization	Volatile organic compounds are taken up and transpired. Some recalcitrant organic compounds are more easily degraded in the atmosphere (photodegradation).	Chlorinated solvents (tetrachloromethane and trichloromethane), organic VOCs, BTEX, MTBE

In practice, only a few of these compounds have been proven to be feasibly treated in pilot scale field treatments. Most have been proven feasible in laboratory pilots. A few are extrapolated as being feasible from studies of similar compounds.

Table 1-2: Types of Phytoremediation for Inorganic Compounds

Type of Phytoremediation	*Process Involved*	*Contaminant Treated**
1 - Phytostabilization	Plants control pH, soil gases, and redox conditions in soil to immobilize contaminants. Humification of some organic compounds is expected.	Proven for heavy metals in mine tailing ponds
2 - Rhizofiltration or contaminant uptake	Compounds are taken up or sorbed by roots (or sorbed to algae and bacteria).	Heavy metals and radionuclides
3 - Phytoaccumulation, phytoextraction, or hyperaccumulation	Metals and organic chemicals are taken up by the plant with water, or by cation pumps, sorption, and other mechanisms.	Nickel, zinc, lead, chromium, cadmium, selenium, other heavy metals; radionuclides
4 - Phytovolatilization	Volatile metals are taken up, changed in species, and transpired.	Mercury and selenium

1.3.1 Applicable or Relevant and Appropriate Requirements (ARARs)

Within the Superfund Amendments and Reauthorization Act (SARA) of 1986, Congress essentially translated into law EPA's policy to use other environmental laws to guide response actions. SARA added CERCLA Section 121(d), which stipulates that the remedial standard or level of control for each hazardous substance, pollutant, or contaminant be at least that of any applicable or relevant and appropriate requirement (ARAR) under federal or state environmental law. For example, Clean Water Act restrictions can be applicable to hazardous substances discharged into surface water from a Superfund site. Regulations codified in the National Contingency Plan govern the identification of ARARs and require compliance with ARARs throughout the Superfund response process, including during certain removal actions. All remediation technologies used at Superfund sites are subject to ARARs. Regulators must evaluate the proposed phytoremediation application and determine if it meets federal and state environmental statutes, regulations, and other requirements that pertain to the site

2.0 PHYTOREMEDIATION DESIGN

The design of a phytoremediation system varies according to the contaminants, the conditions at the site, the level of cleanup required, and the plants used (*Phytoremediation*, a Technology Evaluation Report, Schnoor). A thorough site characterization should provide the needed data to design any type of remediation system. The source of the pollution may need to be removed if phytoremediation is the chosen technology for remediation. Clearly, phytoextraction has different design requirements than phytostabilization or rhizodegradation. Nevertheless, it is possible to specify a few design considerations that are a part of most phytoremediation efforts. Site characterization data will provide the information required for the designer to develop a properly functioning system. The design considerations include:

- Contaminant levels
- Plant selection
- Treatability
- Irrigation, agronomic inputs (P, N, K, salinity, Zinc etc.) and maintenance
- Groundwater capture zone and transpiration rate
- Contaminant uptake rate and clean-up time

2.1 Contaminant Levels

During the site characterization phase, the concentration level of the contaminants of concern will be established. High levels of contamination may eliminate phytoremediation as a treatment option. Plants are not able to treat all contaminants. The composition of organic compounds (structure, log Kow, degree of weathering, and boiling point range) and degree of adsorption are important factors in phytoremediation. It is important to understand the range of contaminants that can be treated using phytoremediation (see Treatability below). In addition to knowing the contaminants and their concentrations, the depth of the contaminants must be known.

2.2 Plant Selection

Plants are selected according to the application and the contaminants of concern. For phytotransformation of organic compounds, the design requirements are that vegetation is fast growing and hardy, easy to plant and maintain, utilizes a large quantity of water by evapotranspiration, and transforms the contaminants of concern to nontoxic or less toxic products. In temperate climates, phreatophytes (e.g., hybrid poplar, willow, cottonwood, aspen) are often selected because of fast growth, a deep-rooting ability down to the level of groundwater, large transpiration rates, and the fact that they are native throughout most of the country. A screening test or knowledge about plant attributes from the literature will aid the design engineer in the selection of plants.

Plants used in phytoextraction include sunflowers and Indian mustard for lead; *Thlaspi* spp. (pennycress) for zinc, cadmium, and nickel; and sunflowers and aquatic plants for radionuclides. Aquatic plants are used in constructed wetlands applications. The two categories of aquatic plants used are emergent and submerged species. Emergent vegetation transpires water and is easier to harvest if required. Submerged species do not transpire water but provide more biomass for the uptake and sorption of contaminants.

2.3 Treatability

Treatability or plant screening studies are recommended prior to designing a phytoremediation system. If the decision tree flowcharts indicate phytoremediation is an applicable technology for a site, contact a plant scientist to assist in the treatability studies. Treatability studies assure concerned parties that the phytoremediation system will achieve the desired results. Toxicity and transformation data are obtained in treatability studies. Treatability studies assess the fate of the contaminants in the plant system. Different concentrations of contaminant are tested with proposed plant species. Volatile organic compounds are often transpired to the atmosphere by plants. Calculations will predict the amount and type of material transpired by the plants.

2.4 Irrigation, Agronomic Inputs, and Maintenance

Irrigation of the plants ensures a vigorous start to the system even in drought. Hydrologic modeling may be required to estimate the rate of percolation to groundwater during irrigation conditions. Irrigation should be withdrawn if the area receives sufficient rainfall to sustain the plants.

Agronomic inputs include the nutrients necessary for vigorous growth of vegetation and rhizosphere microbes. The soil must be analyzed and then items such as nitrogen, potassium, phosphorous, aged manure, sewage sludge compost, straw and/or mulch are added as required to ensure the success of the plants. Maintenance of the phytoremediation system may include adding fertilizer, agents to bind metals to the soil, or chelates to assure plant uptake of the contaminants. Replanting may be required due to drought, disease, or insects or animals killing off plants.

2.5 Groundwater Capture Zone and Transpiration Rate

For applications involving groundwater remediation, a capture zone calculation can be used to estimate whether the phytoremediation pump (trees) can be effective at entraining the plume of contaminants. The goal is to create a water table depression where contaminants will flow to the vegetation for uptake and treatment. Organic contaminants are not taken up at the same concentration as in the soil or groundwater. Membranes at the root surface reduce the uptake rate of the contaminant.

2.6 Contaminant Uptake Rate and Clean-up Time

Although it is possible to estimate the uptake rate of contaminants, the calculation is beyond the scope of this decision tree document. The Ground-Water Remediation Technologies Analysis Center (GWRTAC) Technology Evaluation Report *Phytoremediation*, by Jerald L. Schnoor, (www.gwrtac.org) describes how to determine the contaminant uptake rate and cleanup time.

3.0 GROUNDWATER DECISION TREE INFORMATION

The information listed below combined with the Groundwater Decision Tree Flowchart will assist the user in determining if the contaminated site is a candidate for phytoremediation.

1. Site characterization will determine if the groundwater and contaminants are within root depth range of the plants or trees to be used. Typically this is 10–20 feet below ground surface (bgs). Site characterization will determine the physical properties and nutrient requirements of the soil.

2. If the groundwater is to be pumped to the surface and then applied to the plants (some form of irrigation), state regulations must be reviewed. There may be restrictions on the use of contaminated water for irrigation.

3. Greenhouse or pilot field studies of selected plants are recommended to determine the ability of candidate plant species to survive in the contaminated environment. The plant that reacts best is based upon a number of different requirements.

4. The accumulation of waste in the plants may present a problem with contaminants entering the food chain. The relative concentrations of contaminants in the plant tissue must be determined. Proper harvest and disposal methods must be developed and approved by regulatory agencies.

5. Transpiration of heavy metals such as mercury or organic contaminants such as TCE must be evaluated to determine if the process creates a hazard to human health or the environment.

6. Generally the octanol-water partition coefficient (log Kow) of organic contaminants must be between 1 and 3.5 (moderately hydrophobic organic chemicals) to be susceptible to uptake by plants. Hydrophobic chemicals (log Kow > 3.5) are bound too strongly to roots and soil to be translocated within the plants. Water-soluble chemicals (log Kow < 1.0) are neither sufficiently sorbed to roots nor actively transported through plant membranes (Briggs et. al., 1982).

7. Hydraulic control is a form of containment. Groundwater contaminant plume control may be achieved through water consumption in plants that increase evaporation and transpiration from a site. Trees and other plants can be used as inexpensive solar pumps that use the energy of the sun to raise contaminated water to the surface. These plants may also have enzymes or other factors capable of reacting with, and in many plants completely degrading, some chemicals like munitions and chlorinated solvents.

8. Phytoremediation may take longer than traditional methods to reach final cleanup levels. Site characterization data should allow phytoremediation designers to estimate the cleanup time.

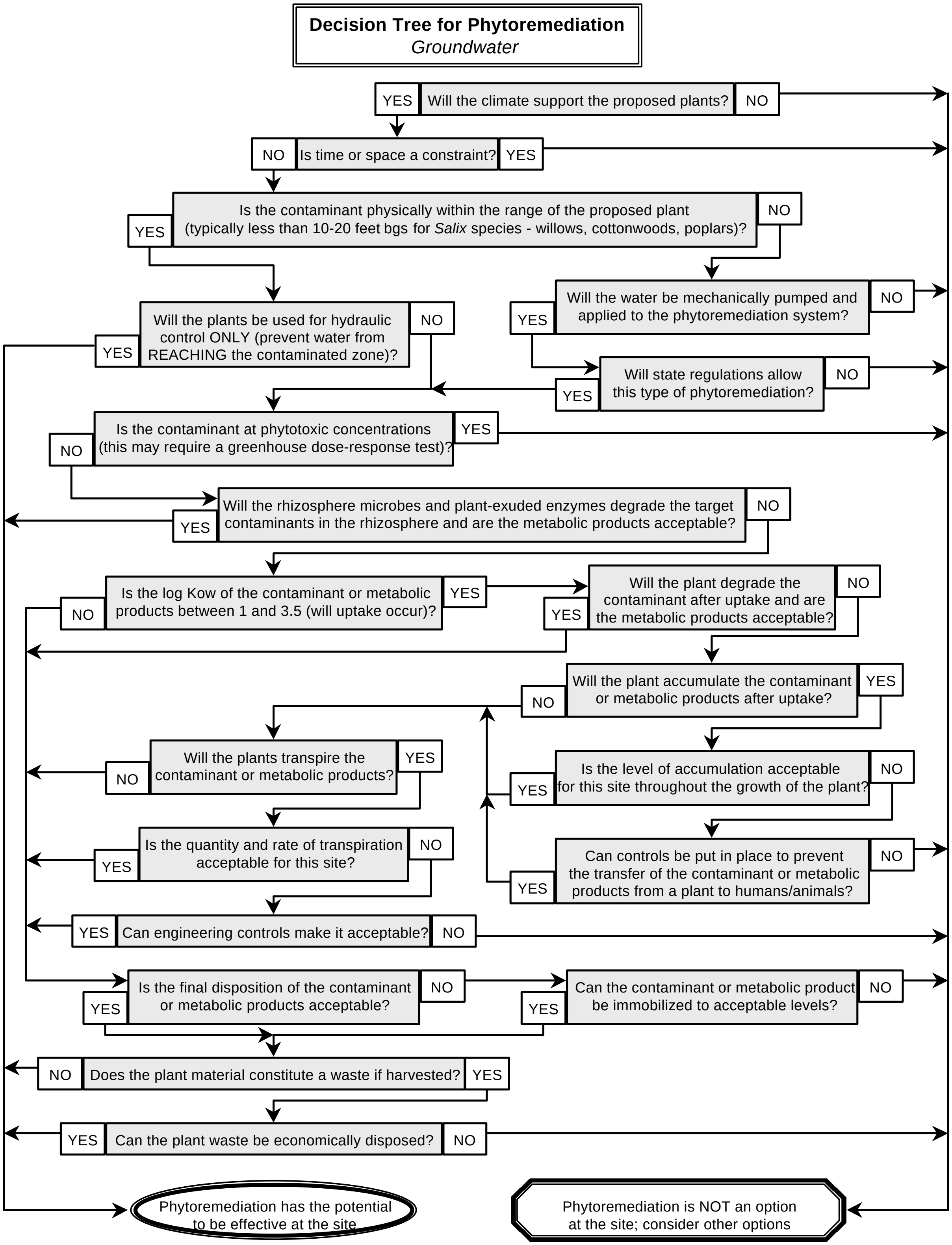


Figure 3-1: Groundwater Decision Tree

4.0 SOIL DECISION TREE INFORMATION

The information listed below combined with the Soil Decision Tree Flowchart will assist the user in determining if the contaminated site is a candidate for phytoremediation.

1. A thorough site characterization will determine if the contaminant or contaminants are within the range of the plants. Typically this is 1–2 feet below ground surface (bgs). Research conducted in 1999 by Olsen and Fletcher (University of Oklahoma) has shown destruction of polycyclic aromatic hydrocarbons (PAHs) to depths greater than 3.5 feet (44 inches) using mulberry trees. The mulberry trees were 12 years old growing in a former waste disposal basin. More research is needed to examine deep-rooting plants' ability to remediate contaminants in soil.

2. Phytoremediation may take longer than traditional methods to reach final cleanup levels. Site characterization data should allow the phytoremediation designer to estimate the cleanup time. The designer will also make a determination if the size of the site will support phytoremediation.

3. Greenhouse or pilot field studies of selected plants are recommended to determine the ability of candidate plant species to survive in the contaminated environment. The plant that will be the most effective for phytoremediation is determined based upon a number of different requirements.

4. Plants can remove metals, radionuclides, and certain organic compounds (volatile, water-soluble petroleum hydrocarbons) by direct uptake. Phytostabilization refers to holding contaminated soils in place by vegetation and immobilizing toxic contaminants.

5. Plant growth in the rhizosphere increases organic carbon, bacteria, and mycorrhizal fungi—all factors that encourage the degradation of organic chemicals. The addition of plant root systems creates an ecology that is suitable for bioremediation.

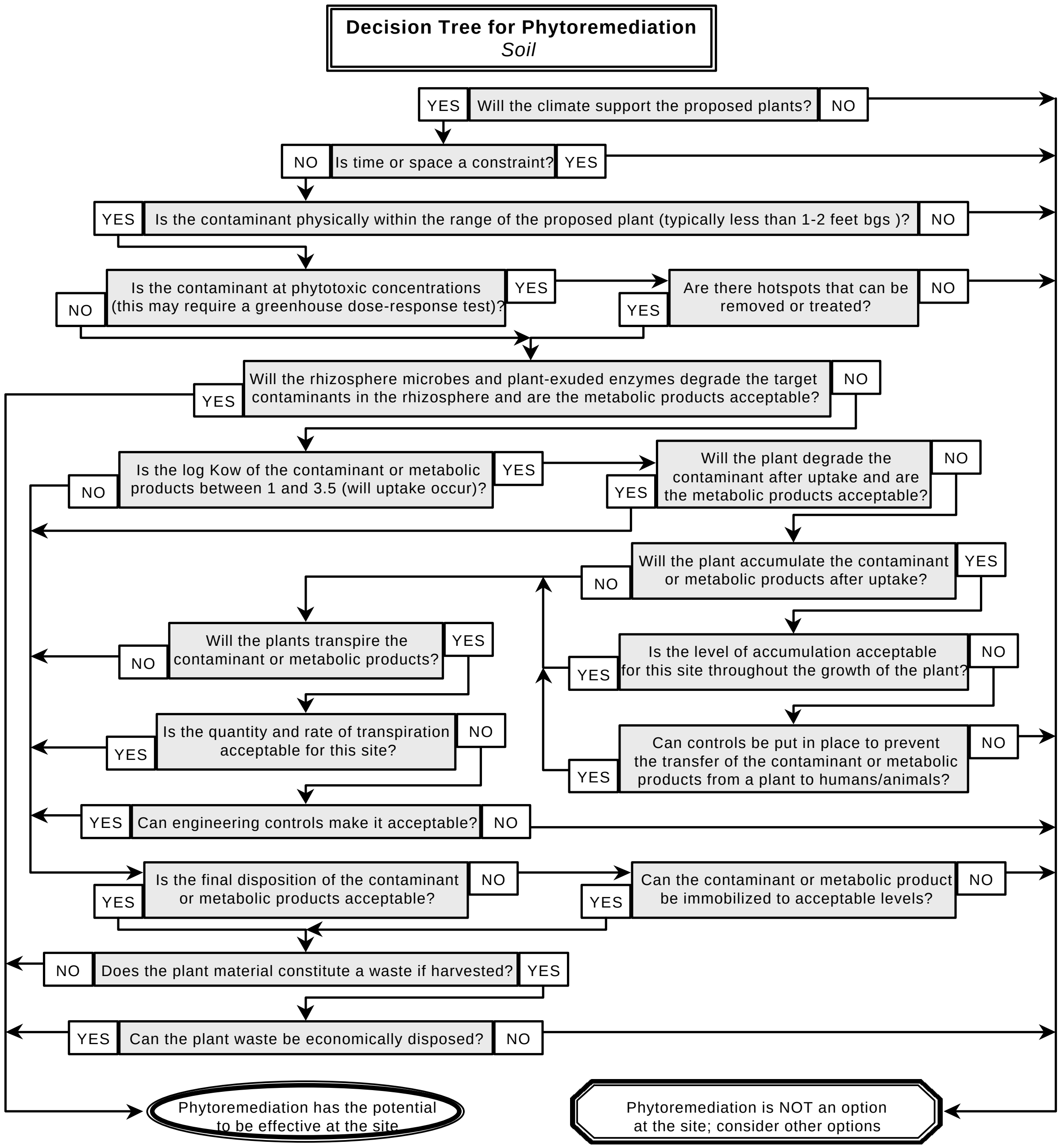
6. Oxygen, water, and carbon transport mechanisms can vary among plant species. Plants supply oxygen to the root zone, and root turnover is a key mechanism that adds organic carbon. Oxygen pumped to the root zone by the plant ensures aerobic transformations. Laboratory studies have shown seedlings can contribute considerable quantities of oxygen to the roots (0.5 mol O_2 per m^2 of surface area per day) (Shimp et al.).

7. If there are hot spots (areas toxic to plants), it must be determined if they can be economically treated or removed. Removal of phytotoxic hot spots will make phytoremediation an option to "polish" the site and remove the remaining contamination.

8. Plants that transpire heavy metals, such as mercury, or organic contaminants, such as TCE, may create a hazard to human health or the environment. The transpiration products will need to be evaluated to determine if they are a hazard.

9. The accumulation of waste in the plants may present a problem with contaminants entering the food chain or cause the plants to become a waste disposal issue. The relative concentrations

of contaminants in the plant tissue must be determined and proper disposal methods established and approved by regulatory personnel.



5.0 SEDIMENT DECISION TREE INFORMATION

The information listed below combined with the Sediment Decision Tree Flowchart will assist the user in determining if the contaminated site is a candidate for phytoremediation.

1. Dredging activities and dredged sediments (also known as dredge spoils) are regulated by the US Army Corps of Engineers. Dredged sediments will have regulatory requirements beyond those for groundwater and soil.

2. It can take up to 20 years (typically 5–10 years) for the spoil material to dry enough for final disposal. The spoil material is held in holding ponds behind large dykes (up to 50 feet in height). Innovative use of thinner “lifts” of dredge spoil and lower dikes allows the material to settle out faster.

3. Dredge spoils normally lack organic matter because organic matter is washed out by the process that creates the spoils.

4. Dredge spoils normally pick up salt from seawater, and they become highly acidic when removed from the water and exposed to the air.

5. If the contaminants are to be treated in place or in a constructed wetland, state regulations must be checked. Different regulatory agencies may be involved in constructed wetlands as well as in-place treatment.

6. There may be public opposition to treating dredge spoils as a soil or creating a wetland with the spoil material. There has been a great deal of public opposition to having dredge spoils used for other projects. The normal course of events is to have the dredge spoils dumped at sea or landfilled.

7. Site characterization is needed to determine if the contaminant is within the range of the plants to be used. More research is needed to examine the ability of deep-rooting plants to remediate contaminants in sediments.

8. Metals, radionuclides, and certain organic compounds (volatile, water-soluble petroleum hydrocarbons) can be removed by direct uptake into the plant tissue.

9. Greenhouse or pilot field studies of selected plants are recommended to determine the ability of candidate plant species to survive in the contaminated environment. The plant that will be the most effective for phytoremediation is based upon a number of different requirements.

10. If there are hot spots (areas toxic to plants), it must be determined if they can be economically treated or removed. Removal of phytotoxic hot spots will make phytoremediation an option to “polish” the site and remove the remaining contamination.

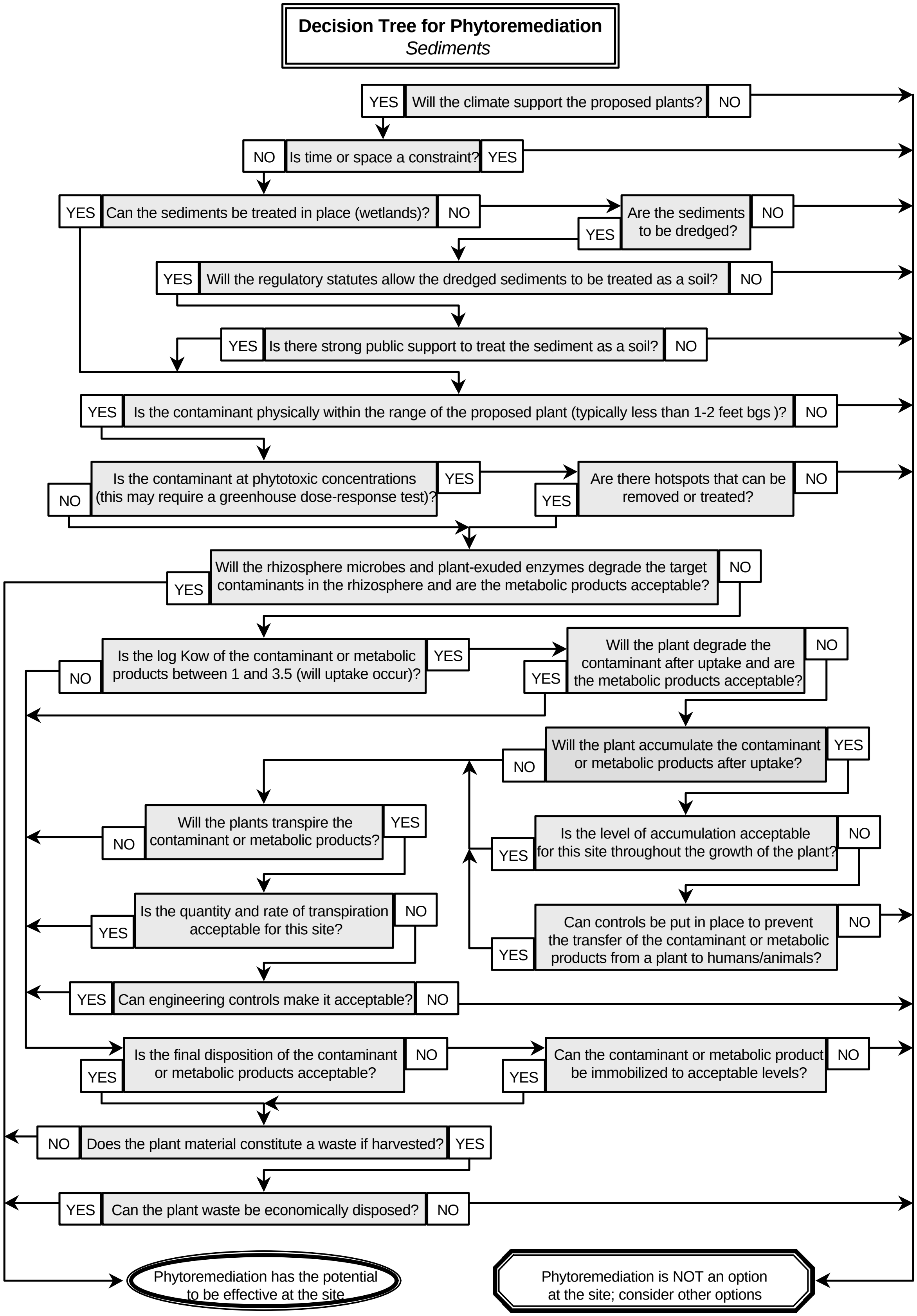
11. The accumulation of waste in the plants may present a problem with contaminants entering the food chain or cause the plants to become a secondary waste disposal issue. The relative concentrations of contaminants in the plant tissue must be determined and proper disposal methods established and approved by regulatory personnel.

12. Plants that transpire heavy metals, such as mercury, or organic contaminants, such as TCE, may create a hazard to human health or the environment. The transpiration products will require evaluation to determine if they are a hazard.

13. Plant growth in the rhizosphere increases organic carbon, bacteria, and mycorrhizal fungi—all factors that encourage the degradation of organic chemicals. The addition of plant root systems creates an ecology that is suitable for bioremediation.

14. Oxygen, water, and carbon transport mechanisms can vary among plant species. Plants supply oxygen to the root zone, and root turnover is a key mechanism that adds organic carbon. Oxygen pumped to the root zone by the plant ensures aerobic transformations. Laboratory studies have shown seedlings can contribute considerable quantities of oxygen to the roots (0.5 mol O_2 per m^2 surface area per day) (Shimp et al.).

15. Phytostabilization refers to holding contaminated sediments in place by vegetation and immobilizing the toxic contaminants.


Decision Tree for Phytoremediation
Sediments
Will the climate support the proposed plants?
YES
NO
Is time or space a constraint?
NO
YES
Can the sediments be treated in place (wetlands)?
YES
NO
Are the sediments to be dredged?
NO
YES
Will the regulatory statutes allow the dredged sediments to be treated as a soil?
YES
NO
Is there strong public support to treat the sediment as a soil?
YES
NO
Is the contaminant physically within the range of the proposed plant (typically less than 1-2 feet bgs)?
YES
NO
Is the contaminant at phytotoxic concentrations (this may require a greenhouse dose-response test)?
NO
YES
Are there hotspots that can be removed or treated?
YES
NO
Will the rhizosphere microbes and plant-exuded enzymes degrade the target contaminants in the rhizosphere and are the metabolic products acceptable?
YES
NO
Is the log Kow of the contaminant or metabolic products between 1 and 3.5 (will uptake occur)?
NO
YES
Will the plant degrade the contaminant after uptake and are the metabolic products acceptable?
YES
NO
Will the plant accumulate the contaminant or metabolic products after uptake?
NO
YES
Will the plants transpire the contaminant or metabolic products?
NO
YES
Is the level of accumulation acceptable for this site throughout the growth of the plant?
YES
NO
Is the quantity and rate of transpiration acceptable for this site?
YES
NO
Can controls be put in place to prevent the transfer of the contaminant or metabolic products from a plant to humans/animals?
YES
NO
Can engineering controls make it acceptable?
YES
NO
Is the final disposition of the contaminant or metabolic products acceptable?
YES
NO
Can the contaminant or metabolic product be immobilized to acceptable levels?
YES
NO
Does the plant material constitute a waste if harvested?
NO
YES
Can the plant waste be economically disposed?
YES
NO
Phytoremediation has the potential to be effective at the site
Phytoremediation is NOT an option at the site; consider other options

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Sonoma Baylands: Creating an Environmental Benefit out of The San Francisco Bay Dredging Crisis, Marcus, Laurel, available at http://www.epa.gov/cookbook/page94.html

Ecolotree Ideal Project Description, available at http://www.Ecolotree.com/page4.htm

The Center for Public Environmental Oversight (CPEO) Web site provides information on phytoremediation http://www.cpeo.org/techtree/ttdescript/phytrem.htm

Information relating to phytoremediation--an innovative technology for remediating sites contaminated with hazardous substances, available from the Hazardous Substance Research Center at Kansas State University can be found at: http://www.engg.ksu.edu/HSRC/phytorem/

APPENDIX A

Phytoremediation Glossary

A glossary of terms related to phytoremediation (remediation using green plants)

Absorption: The process of one substance actually penetrating into the structure of another substance. This is different from **adsorption**, in which one substance adheres to the surface of another substance.

Adsorption: The physical process occurring when liquids, gases or suspended matter adhere to the surfaces of, or in the pores of, an adsorbent material. Adsorption is a physical process which occurs without chemical reaction.

ARAR: Applicable or Relevant and Appropriate Requirement.

Aerobe: An organism that can grow in the presence of air or free oxygen.

Aerobic: An environment that has a partial pressure of oxygen similar to normal atmospheric conditions.

Anaerobic: An environment without oxygen or air.

Anaerobe: An organism that grows in the absence of oxygen or air.

Anoxic: An atmosphere greatly deficient in oxygen.

Bacteria: A group of diverse and ubiquitous prokaryotic single-celled microorganisms.

Bioaccumulation: Intracellular accumulation of environmental pollutants such as heavy metals by living organisms.

Biodegradation: The breakdown of organic substances by microorganisms.

Bioremediation: The process by which living organisms are used to degrade or transform hazardous organic contaminants.

Bound residues: Chemical contaminants that are not extractable from plant tissues by conventional methods (covalent bonding, polymerization, or lignification within the plant).

Brownfield: An abandoned, idled, or under-used industrial or commercial facility where expansion or redevelopment is complicated by a real or perceived environmental contamination.

BTEX: Benzene, toluene, ethylbenzene, and xylenes.

Capillary fringe: The porous material just above the water table which may hold water by capillarity (a property of surface tension that draws water upward) in the smaller soil void spaces.

Chelates: The type of coordination compound in which a central metallic ion (CO^{2+}, Ni^{2+}, or Zn^{2+}) is attached by covalent bonds to two or more nonmetallic atoms in the same molecule, called ligands. Chelating agents are used to remove ions from solutions and soil.

Creosote: An antifungal wood preservative used frequently to treat telephone poles and railroad ties. Creosote consists of coal tar distillation products, including PHENOLS and PAHs.

DCE: Dichloroethylene includes three isomers 1,1,DCE, 1,2 CisDCE and 1,2 trans DCE.

DNAPL: Dense non-aqueous phase liquid, these liquids are more dense than water .

Enhanced rhizophere biodegradation: Enhanced biodegradation of contaminants near plant roots where compounds exuded by the roots increase microbial biodegradation activity. Other plant processes such as water uptake by the plant roots can enhance biodegradation by drawing contaminants to the root zone.

Enzymes: Proteins that act as biological catalysts. These chemicals produced by living organisms bring about the digestion (breakdown) of organic molecules into smaller units that can be used by living cell tissues.

EPA: United States Environmental Protection Agency

***Ex situ*:** Out of the original position (Excavated).

Exudates: Release of soluble organic matter from the roots of plants to enhance availability of nutrients or as a byproduct of fine root degradation.

Greenhouse study: Studies conducted to evaluate the ability of green plants to grow in toxic soil or water environments. Greenhouse studies are normally conducted during treatability studies.

Groundwater: Water found beneath the surface of the ground. Groundwater is primarily water which has seeped down from the surface by migrating through the interstitial spaces in soils and geologic formations.

Hydroponics: The cultivation of plants by placing the roots in liquid nutrient solutions rather than soil.

***In situ*:** In place, without excavation.

ITRC: Interstate Technology and Regulatory Cooperation (Work Group).

LNAPL: Light non-aqueous phase liquid, these liquids are lighter than water.

Log Kow: The octanol-water partition coefficient is a dimensionless constant which provides a measure of how an organic compound will partition between an organic phase and water. A low

log Kow indicates that a chemical readily partitions into a water phase while a high log Kow indicates that the chemical prefers to stay in the organic phase. It provides an indication of the quantity of the chemical that will be taken up by the plants.

Microorganisms: Includes bacteria, algae, fungi and viruses.

Mineralization: The breakdown of organic matter to inorganic materials (such as carbon dioxide and water) by bacteria and fungi.

Nutrients: Elements or compounds essential as raw materials for organism growth and development. Nitrogen, phosphorous, potassium, and numerous other mineral elements are essential plant nutrients.

Organic pump: Uptake of large quantities of water by plant (trees) roots and translocation into the atmosphere to reduce a flow of water. Used to keep contaminated groundwater from reaching a body of water, or to keep surface water from seeping into a capped landfill and forming leachate.

PAH: Polynuclear aromatic hydrocarbon. Multi-ring compounds found in fuels, oils, and **Creosote**. These are also common combustion products.

Parts per billion (ppb): A measure of proportion by weight which is equivalent to one unit weight of solute (dissolved substance) per billion unit weights of the solution (ug/kg or µg/kg). One liter of water weighs one billion micrograms, and one ppb is the equivalent of one microgram per liter (ug/L or µg/L) when used for water analysis.

Parts per million (ppm): A measure of proportion by weight which is equivalent to one unit weight of solute (dissolved substance) per million unit weights of the solution (mg/kg). One liter of water weighs one million milligrams, and one ppm is equal to one milligram per liter (mg/L) for water analysis.

PCBs: Polychlorinated biphenyls.

PCE: (Perchloroethylene): Tetrachloroethylene.

PCP: Pentachlorophenol.

Phenol: Carbolic acid (C_6H_5OH). Phenols and substituted phenols are used as antimicrobial agents in high concentrations.

Phytoaccumulation: See **Phytoextraction**.

Phytodegradation: A process in which plants are able to degrade (break down) organic pollutants through their metabolic processes.

Phytoextraction: Use of plants to extract contaminants (such as metals) from the environment (especially soil). When the plants are saturated with contaminants they are harvested.

Phytomining: Use of plants to extract inorganic substances of economic value (precious metals, etc.)

Phytoremediation: Use of plants to remediate contaminated soil, sediments, surface water, or groundwater.

Phytostabilization: Use of soil amendments and plants to reduce bioavailability and offsite migration of contaminants.

Phytotoxic: Harmful to plants.

Phytovolatilization: Use of plants to volatilize contaminants (solvents, etc.) from soil or water (also known as **Phytotransformation**).

Rhizofiltration: Uptake of contaminants by the roots of plants immersed in water. When the roots are saturated with contaminants, they are harvested.

Rhizosphere: Soil in the area surrounding plant roots that is influenced by the plant root. Typically a few millimeters or at most centimeters from the plant root. Important because this area is higher in nutrients and thus has a higher and more active microbial population.

Rhizosphere bioremediation: Using the bacteria, fungi and protozoans that occur in the biologically rich zone of the immediate vicinity around plant roots to treat organic contaminants.

Root turnover: The release and decay of fine roots in the soil profile.

TCE: Trichloroethylene.

TCLP: Toxicity Characteristic Leaching Procedure, an EPA developed test to determine the toxicity of a chemical.

TPH: Total petroleum hydrocarbons.

Toxic substances: Chemical elements and compounds such as lead, benzene, dioxin, and others that have toxic (poisonous) properties when exposure by ingestion, inhalation or absorption into the organism occurs. There is a large variation in the degree of toxicity among toxic substances and in the exposure levels that induce toxicity.

Translocation: Cellular transport through the plant vascular system (xylem) from roots to other plant tissues: roots → shoots → branches → leaves.

Transpiration: The plant based process involving the uptake, transport and eventual vaporization of water through the plant body.

Vadoze zone: Unsaturated zone of soil above the groundwater, extending from the bottom of the capillary fringe all the way to the soil surface.

Volatile organic compounds: Synthetic organic chemicals capable of becoming vapor at relatively low temperatures.

Water table: The level at the top of the zone of groundwater saturation.

Water table depression: A drop in water table level caused by mechanical or natural groundwater pumping

Zone of saturation: The layer in the ground in which all available interstitial voids (cracks, crevices, holes) are filled with water. The level of the top of this zone is the **water table.**

APPENDIX B

ITRC Contacts, ITRC Fact Sheet, ITRC Product List, and Document Evaluation Survey

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